Modeling and Parameterization Study of Radiance in a Dynamic Ocean

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LONG-TERM GOAL

The primary focus of this research is to integrate dynamical processes of wave and turbulence in the upper ocean surface boundary layer (SBL) into a physics-based computational capability for the time-dependent radiative transfer (RT) in the ocean. The combined capability we develop will provide direct forward predictions of the radiance distributions in the upper ocean. We aim to use this capability for understanding the basic features and dependencies of oceanic radiance on the wave environment, to provide guidance and cross-calibration for field measurements, and to validate and benchmark existing and new theories. As an ultimate goal, the proposed direct simulation also provides a framework, in conjunction with sensed radiance data, for the optimal reconstruction of salient features of the ocean surface and the above-water scene.

OBJECTIVES

This project is for the data analysis as part of the modeling effort in the Radiance in a Dynamic Ocean (RaDyO) DRI. The scientific and technical objectives of our research are to:

- develop numerical capabilities for the direct simulation of nonlinear capillary-gravity waves (CGW)
- develop numerical capabilities for free-surface turbulence (FST) and the resultant surface roughness
- develop direct simulations of RT in the presence of SBL processes of wave and turbulence
- obtain validations and cross-calibrations against field measurements
- use numerical tools of forward prediction to understand and characterize the radiance distribution in terms of the SBL dynamical processes, and to parameterize and model radiance transport and distributions
- develop inverse modeling for the reconstruction of free-surface properties and objects using measured RT data and direct simulation

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APPROACH

We develop a simulation approach based on direct physics-based simulations and modeling to solve the problem of ocean RT in a dynamic SBL environment that includes CGW and FST. The complex dynamic processes of the ocean SBL, the nonlinear CGW interactions, and the development and transport of FST are modeled using physics-based computations. The modeling of these hydrodynamic processes is coupled with the computation of radiative transfer.

For the nonlinear gravity-capillary wavefield evolution, we employ an efficient phase-resolved computational approach. With this approach, we obtain detailed spatial and temporal information of the wavefield during its nonlinear evolution. This computational tool is based on an efficient high-order spectral (HOS) method for direct simulations of nonlinear gravity wavefield evolution. HOS is a pseudo-spectral method developed based on the Zakharov equation and mode-coupling idea. Using direct efficient HOS computations and sensed wave data, we can obtain a phase-resolved reconstruction of nonlinear wavefield evolution based on multi-layer optimizations. With this highly efficient approach, we can capture realistic ocean gravity and capillary wavefield that has a wide range of length scales.

In addition to CGW, radiative transfer at ocean surface is also affected by surface roughness associated with FST. In this study, for moderate wave amplitudes, the FST field is obtained from simulation of the Navier-Stokes equations on a boundary-fitted grid subject to the fully-nonlinear free-surface boundary conditions. When waves steepen and break, an interface capturing method on fixed Eulerian grids is used, with which the air and water together are treated as a system with varying density, viscosity, and diffusivity. Effects of surfactants can be captured through the Plateau-Marangoni-Gibbs effect for which we perform direct simulation of the surfactant transport in the free-surface flow, which is in turn affected by the surfactant-laden boundary conditions. To capture the interaction between FST and CGW, we perform FST simulations with realistic wave inputs obtained from the HOS CGW simulations.

The high-resolution mapping of the free-surface deformation from our direct CGW and FST calculations is coupled into the computation of the underwater radiance field. As light enters the water from the air, they are modified in both propagation direction and intensity at the sea surface subject to Snell's law and Fresnel transmission. The propagation of radiance in the sea water is captured by simulation of radiative transport subject to absorption and multiple scattering. In this study we perform direct simulations of RT in a three-dimensional, temporally-evolving, upper-ocean environment with the key SBL processes being directly simulated. We focus on a Monte Carlo simulation of photons.

Large-scale high-performance computation on parallel computers is used to meet the computational challenges in the CGW, FST, and RT simulations. The suite of codes developed for this research is parallelized using massage passing interface (MPI) based on domain decomposition.

WORK COMPLETED

During the fiscal year of 2012, substantial progresses have been made. A large number of wave, ocean turbulence, and RT simulations have been performed using the geometry of the water surface and the underlying distribution of temperature and salinity from the data base to investigate the physics of

wave-turbulence interaction (Guo & Shen 2012a, b) and the dependence of the light field on the near-surface turbulence and surface waves (Xu et al. 2011, 2012). Research performed includes

- Investigation of wave effect on near-surface turbulence in terms of mean flow, turbulence vorticity, Reynolds stress, and kinetic energy.
- Investigation of the effect of the near-surface turbulence on temperature and salinity concentration.
- Quantification of the turbulence structure of IOPs with empirical models for the dependence of IOPs on temperature and salinity.
- Investigation of the dependence of the underwater irradiance and radiance on the near-surface turbulence and surface waves.
- Investigation of the dependence of the downwelling and upwelling irradiance on the near-surface turbulence and surface waves.
- Development and test of a data-assimilation method based on potential-flow wave simulation for the inverse model of surface geometry using underwater radiance data; and obtaining encouraging progress on the inverse modeling for rotational and viscous flows.

RESULTS

Turbulence transport is important to the variations of scalars (e.g., temperature, salinity, and chlorophyll concentration) near ocean surface, which affect the variations of inherent optical properties (IOPs). We have investigated the dynamics of wave-turbulence interaction and the dependence of the statistics of the irradiance on the near-surface turbulence and surface waves. Figures 1 and 2 show an example of wave effect on turbulence vortices. We use the histogram of vorticity angles to denote the distribution of vortex inclination directions. As shown, the vortices are mainly in the streamwise direction and the vertical direction. Under the forward face of the wave, the strain rate field of the wave stretches the vertical vortices and compresses the horizontal vortices. Because of this effect, under wave crest, vertical vortices reach their maxima while horizontal vortices reach their minima. The opposite happens under the backward face of the wave and wave trough. We can also see that the wave straining effect tilts the vertical vortices clockwisely under the wave crest, and counter-clockwisely under the wave trough. The net effect is that the vertical vortices are tilted into the streamwise direction.

Turbulence in the ocean generates fluctuations in temperature and salinity. This results in variations in IOPs and further changes the underwater light field. Figure 3 shows an example of the instantaneous distributions of the attenuation coefficient, single scattering albedo, and downwelling irradiance on a horizontal plane that is 12.5 m below the water surface. The instantaneous albedo has a distribution pattern similar to that of the attenuation coefficient, and the downwelling irradiance is highly correlated with them.

Lights of different wavelengths have different IOPs, which lead to different radiant energy distributions. In Figure 4, three wavelengths of 400, 500, and 600 nm are compared. On average, the attenuation coefficient is 0.0590 m^{-1}, 0.0535 m^{-1}, and 0.595 m^{-1}, respectively, and the single scattering albedo is 0.62, 0.54, and 0.43, respectively. The cases of 400 nm and 600 nm have respectively the slowest and fastest attenuation rates, as shown in Figure 4(a). The coefficients of variation for the attenuation coefficient and single scattering albedo behave differently from their mean values. We

found that the coefficient of variation of downwelling irradiance is the largest for 400 nm, and is similar between 500 nm 600 nm, as shown in Figure 4(b).

When surface waves and currents co-exist, their interaction substantially increases the complexity of the problem. Figure 5 shows waves propagating along a current and against a current. Top view of the surface elevation is shown in the left two figures, and the corresponding downwelling irradiance distribution on a horizontal plane underwater is shown in the right two figures. When the waves are against a current, the wave-current interaction distorts the waves and enhances turbulence. This effect leads to larger fluctuations in the irradiance.

Figure 6 shows the vertical variations of the mean values and normalized standard deviations of the downwelling irradiance with different temperature dissipation rates. The result shows that higher temperature dissipation rate causes more attenuation, which leads to lower irradiance. The turbulent flow with higher temperature dissipation rates increases the standard deviation of downwelling irradiance slightly.

Figure 7 shows the radiance with different temperature and turbulence dissipation rates. It shows that the dependence of the shape of the radiance distribution on the temperature dissipation rate is small (left figure in Figure 7). But a high temperature dissipation rate causes slight decrease of the radiance for all the polar angles. The dependence of the radiance distribution on the turbulence dissipation rate is obvious (right figure in Figure 7). Higher turbulence dissipation rate causes a slight decrease of radiance at small polar angles.

IMPACT/APPLICATION

This study aims to obtain a fundamental understanding of time-dependent oceanic radiance distribution in relation to dynamic SBL processes. Our work is intended as part of an overall coordinated effort involving experimentalists and modelers. The simulation capabilities developed in our research will provide experimentalists with a powerful tool to validate the observation data. The simulation tool is expected to provide some guidance for field measurement planning. The simulation can also provide whole-field (spatial and temporal) data that helps the interpretation of sparse observation datasets. From simulation, some physical quantities that are difficult to measure can be obtained. What is also significant is that the simulation can be used as a useful tool to isolate physical processes that are coherent in the natural environment. With such analysis, improved understanding, modeling and parameterizations of dependencies of oceanic radiance on SBL environment will be obtained. Our ultimate goal is to use the forward modeling capabilities resulted from this project as a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure. Simulations in this study will provide guidance, cross-calibrations and validations for the experiments. They also provide a framework and a physical basis for the parameterization of oceanic radiative transfer in relation to dynamic surface boundary layer processes.

RELATED PROJECTS

This project is part of the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) DRI (http://www.opl.ucsb.edu/radyo). Our study is performed jointly with Professor Dick K.P. Yue's group at MIT and is in close collaboration with other investigators in this DRI.

PUBLICATIONS

Guo, X. & Shen, L. (2012a), Numerical study of the effect of surface wave on turbulence underneath. Part 1. Mean flow and turbulence vorticity, *Journal of Fluid Mechanics,* submitted.

Guo, X. & Shen, L. (2012b), Numerical study of the effect of surface wave on turbulence underneath. Part 2. Reynolds stresses and kinetic energy, *Journal of Fluid Mechanics,* submitted.

Xu, Z., Guo, X., Shen, L., & Yue, D. K. P. (2012), Radiative transfer in ocean turbulence and its effect on underwater light field, *Journal of Geophysical Research – Oceans,* Vol. 117, C00H18.

Xu, Z., Yue, D. K. P., Shen, L., & Voss, K. J. (2011), Patterns and Statistics of In-Water Polarization under Conditions of Linear and Nonlinear Ocean Surface Waves, *Journal of Geophysical Research – Oceans*, Vol. 116, C00H12.

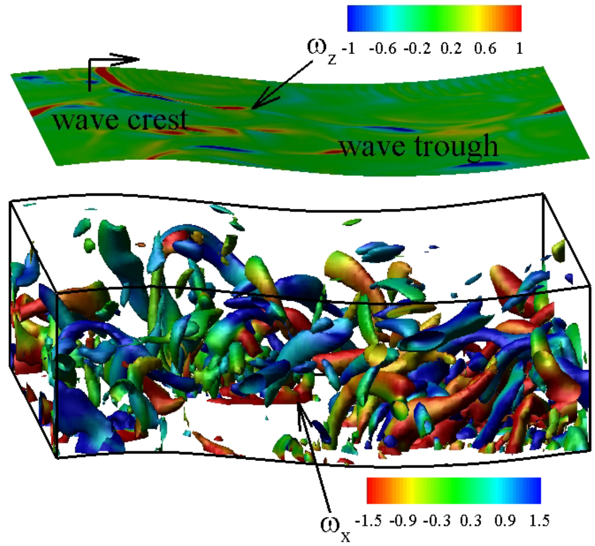

Figure 1. Instantaneous turbulence vortical structures. In the flow, contours of streamwise vorticity are shown on the surface of vortical structures. The wave surface is lifted up for better visualization. Contours of vortical vorticity are shown on the wave surface.

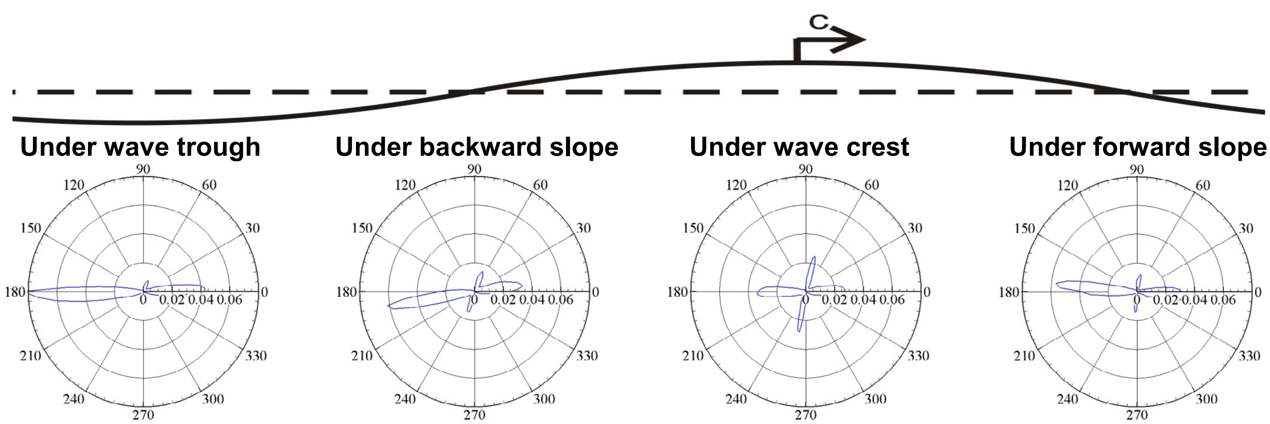

Figure 2. Histogram of vortex inclination angle under the wave trough, backward slope, wave crest, and forward slope.

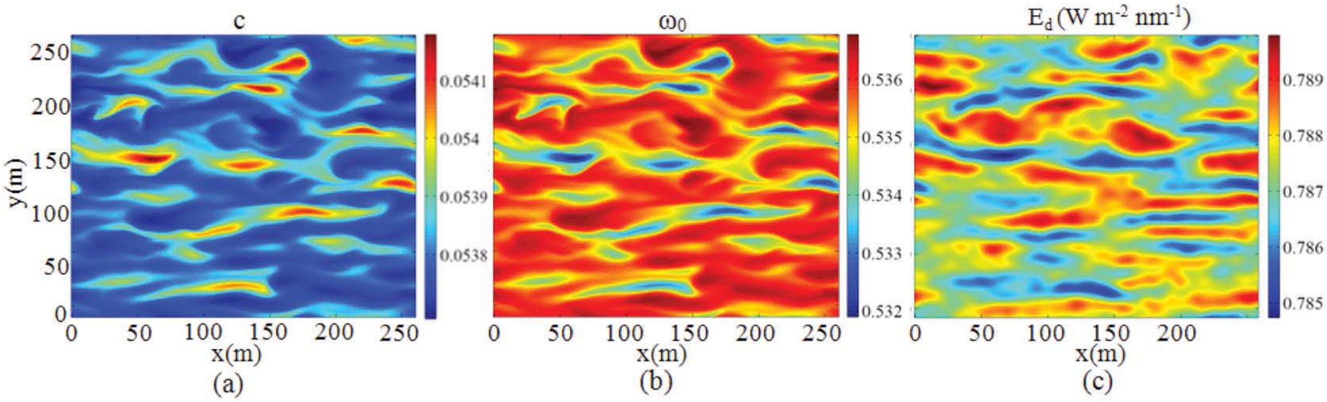

Figure 3. Instantaneous horizontal distributions of (a) the attenuation coeffient, (b) the single scattering albedo, and (c) the downwelling irradiance at the depth of 12.5m under a calm ocean surface with the 500-nm wavelength light, 15^{o}C temperature difference, and 2 ppt salinity difference between the surface and deep ocean.

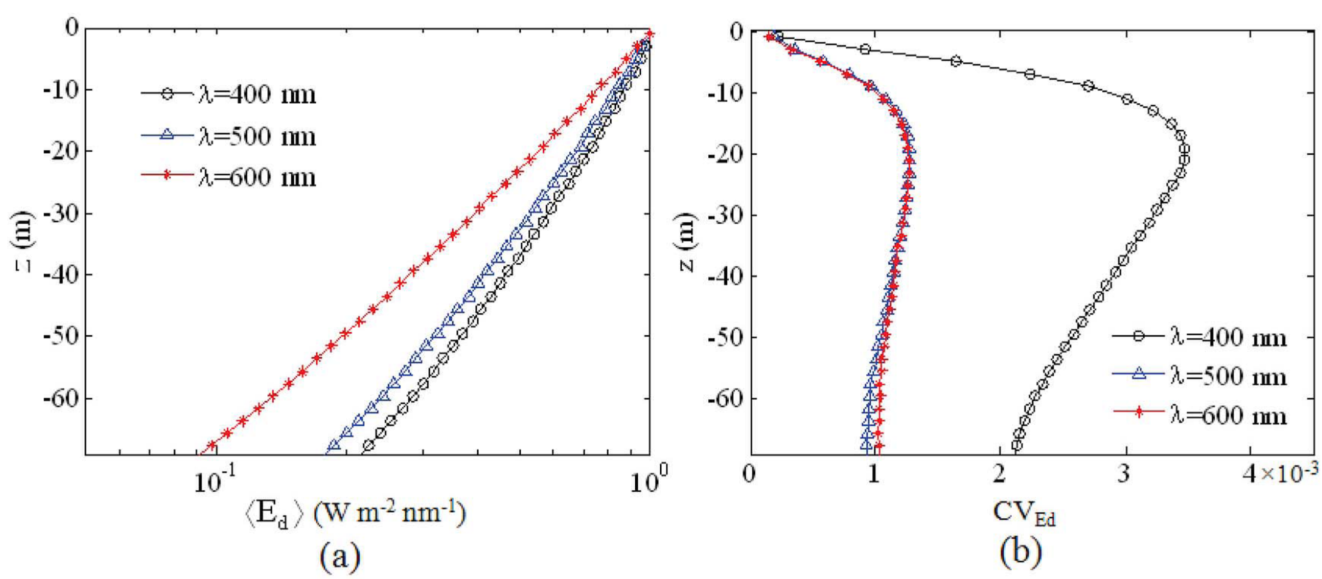

Figure 4. Vertical variations of (a) the mean value and (b) the coefficient of variation of the downwelling irradiance for 400nm (black), 500nm (blue), and 600nm (red) wavelength light under a calm ocean surface with 15^{o}C temperature difference and 2ppt salinity difference between the surface and deep ocean.

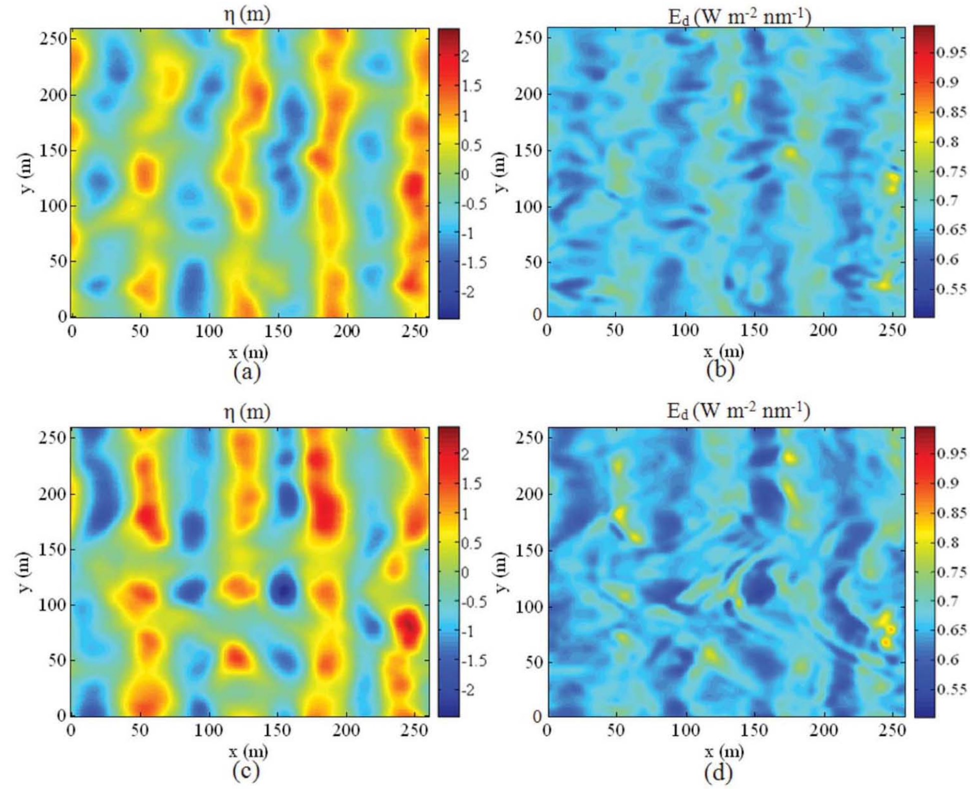

Figure 5. Instantaneous (a) sea surface elevation and (b) downwelling irradiance at the depth of 12.5m under ocean surface wave with $ak = 0.1$ ***propagating in the same direction as the water turbulent current; and instantaneous (c) sea surface elevation and (d) downwelling irradiance at the depth of 12.5m under ocean surface wave with*** $ak = 0.1$ ***propagating in the opposite direction of the water turbulent current. The wavelength of the light is 500nm, the temperature difference is 15 ^{o}C, and the salinity difference is 2ppt between the surface and deep ocean.***

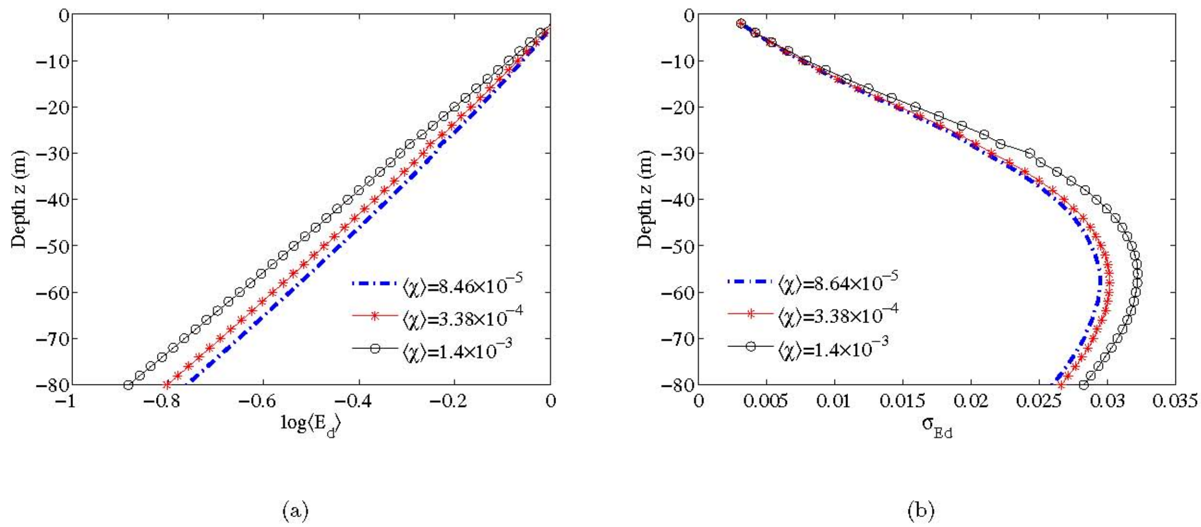

Figure 6. Vertical variations of (a) mean values and (b) normalized standard deviations of downwelling irradiance under progressive ocean waves with $ak = 0.1$ propagating over the near-surface turbulence for cases with different temperature dissipation rates $< \chi >$.

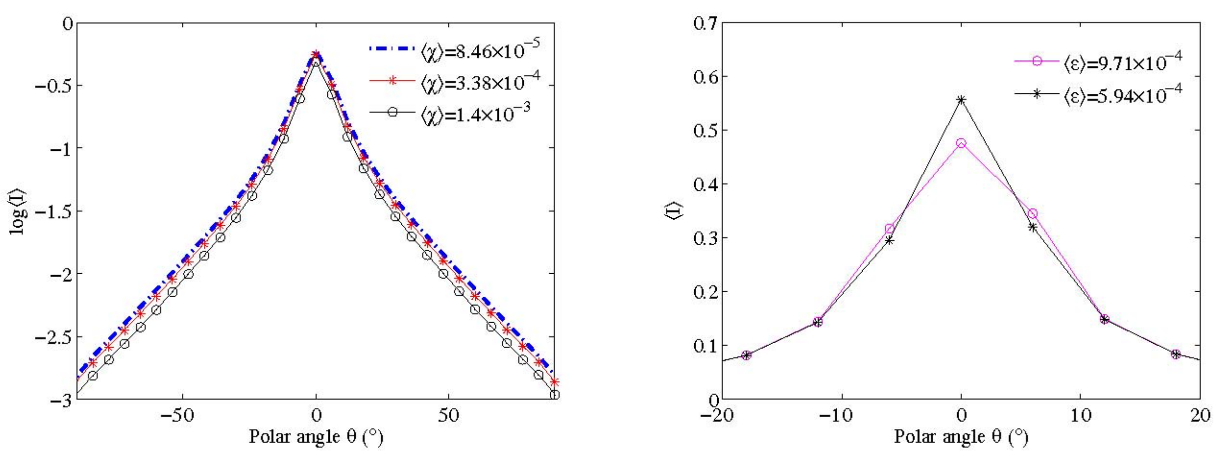

Figure 7. Distributions of mean radiance under ocean waves of $ak = 0.1$ propagating in the same direction as the turbulent current at $80\,m$ below the ocean surface with different temperature dissipation $< \chi >$ (left) and turbulence kinetic energy dissipation rate $< \varepsilon >$ (right).